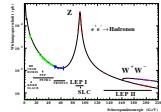


STUDIES OF QCD-RELATED ASPECTS OF EVENT EVOLUTION AT LEP

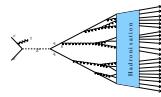
Kristian Harder, DESY Hamburg

21 August, 2002

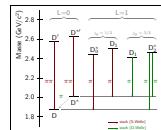
Overview



Introduction to hadronic e^+e^- reactions



Hadronisation of b quarks at OPAL



Investigation of the D meson spectrum at OPAL

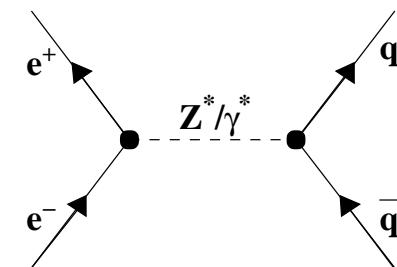
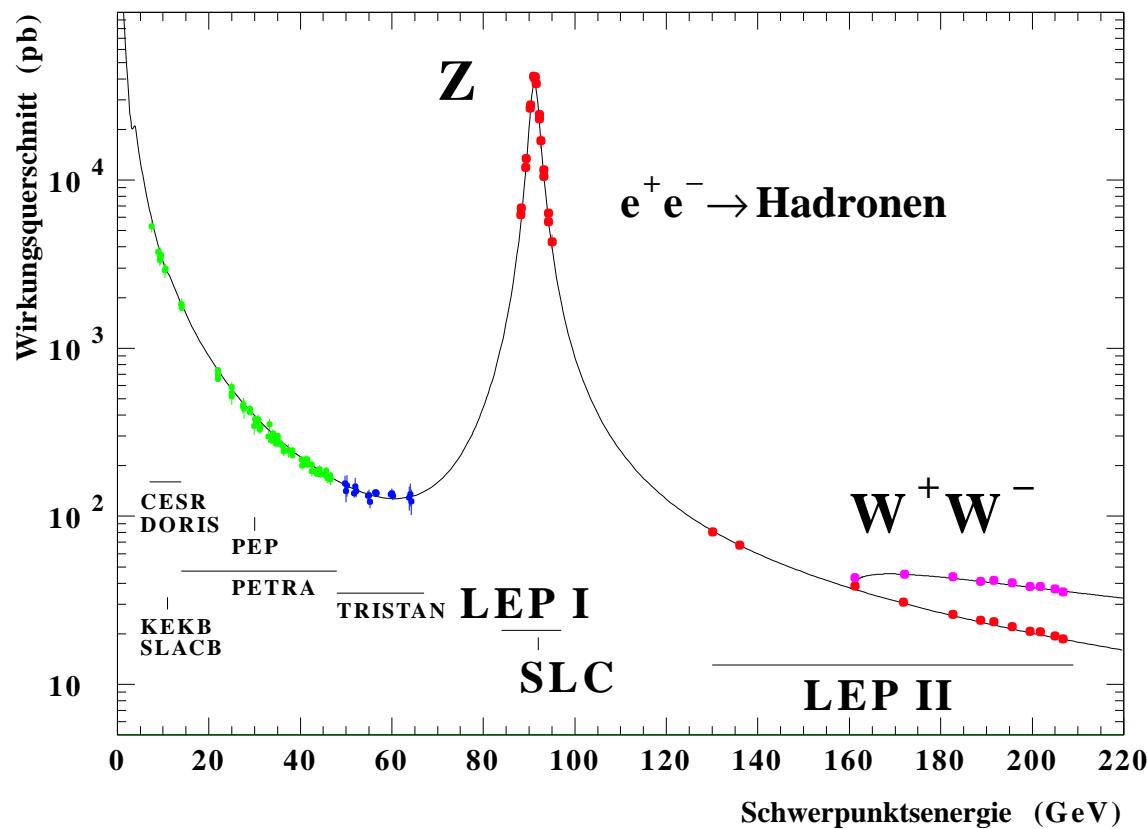


What did we learn?

Production of quarks in e^+e^- annihilations

clean hadronic final state of e^+e^- reactions
large cross-section at $\sqrt{s} \approx 90$ GeV

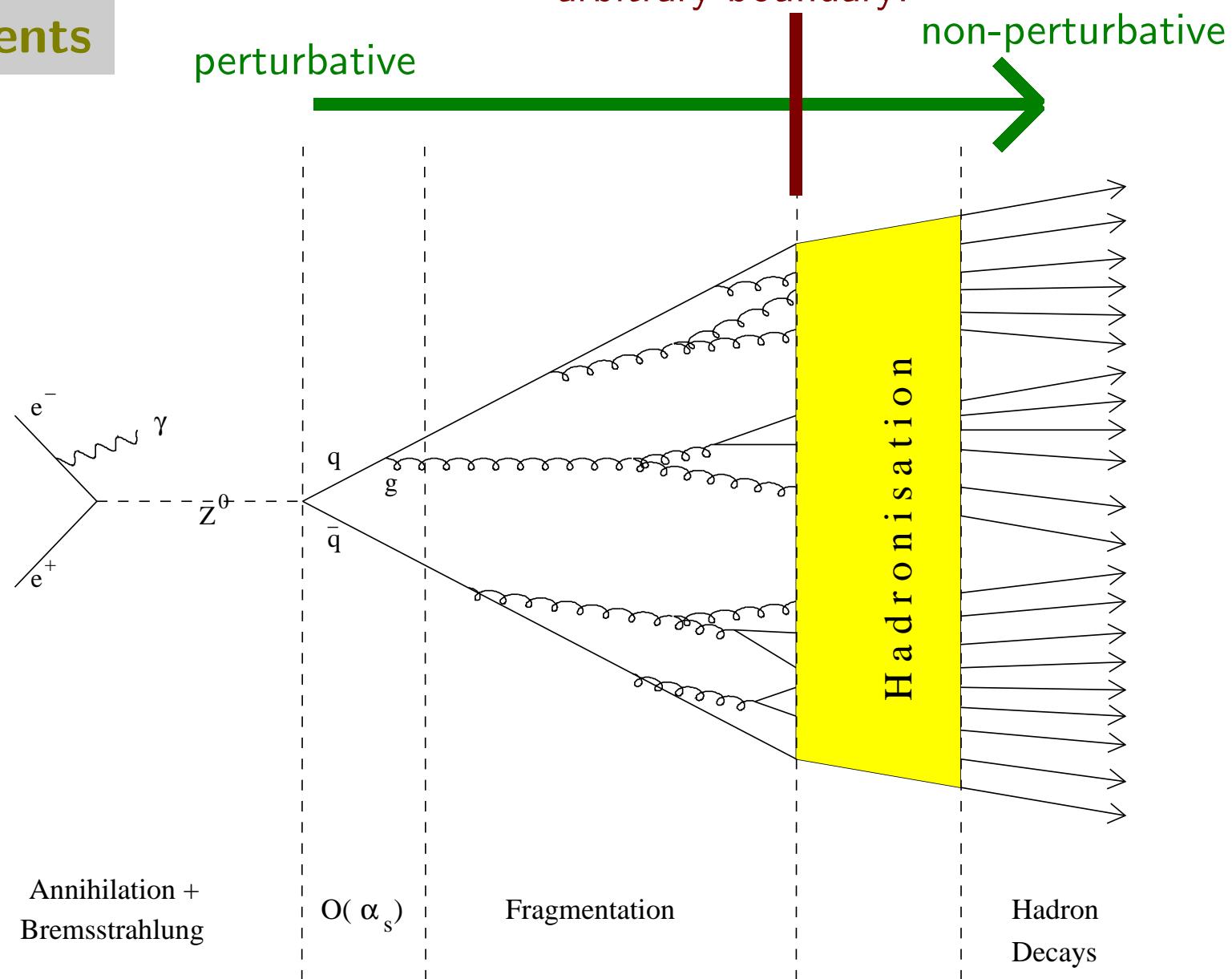
→ LEP1 well suited for QCD studies



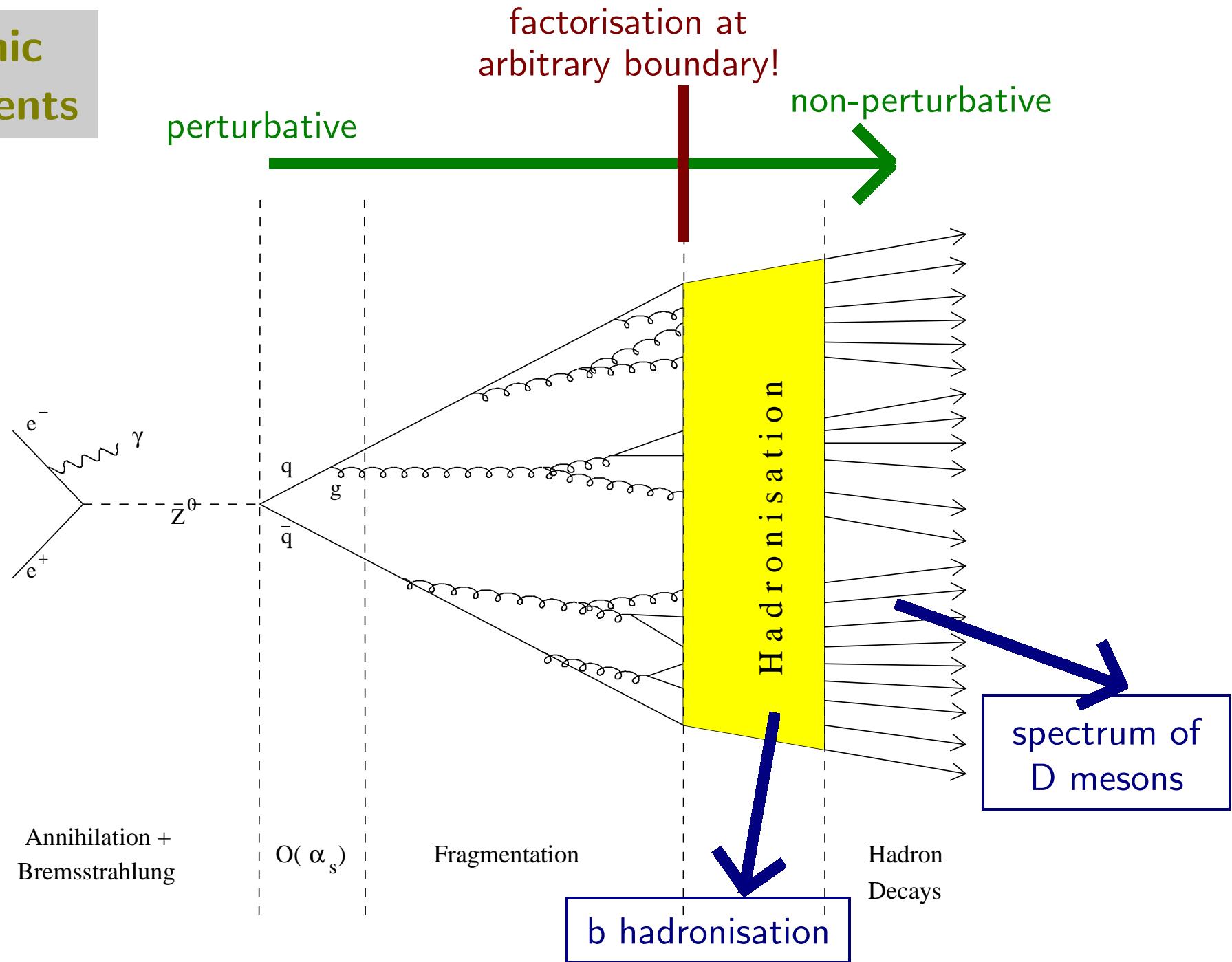
data sample size:
≈ 5 million hadronic Z decays
≈ 2 million b quarks
≈ 2 million c quarks
per experiment

Hadronic e^+e^- events

factorisation at
arbitrary boundary!



Hadronic e^+e^- events

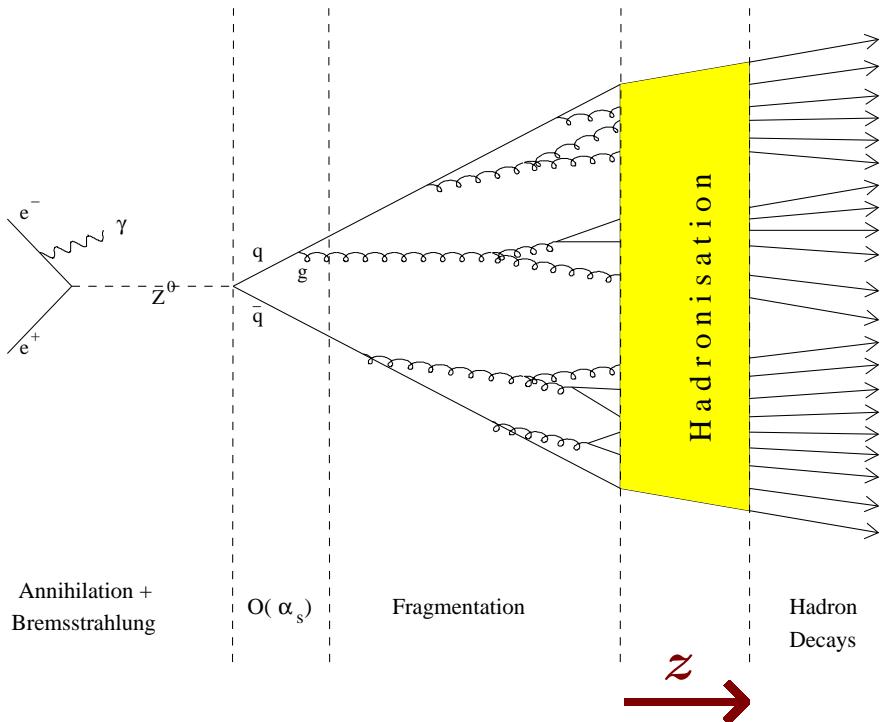


Experimental investigation of the hadronisation process

- can add to theoretical understanding
(distinguish existing models, lead to new ones?)
- reduces systematic uncertainties in many analyses
(e.g. improved Monte Carlo modeling)

Quantitative description of hadronisation

consider energy fraction transferred from quark to hadron



hadronisation models describe $f(z)$:

$$z = \frac{\text{energy of primary hadron}}{\text{energy of quark prior to hadronisation}}$$

model-dependent, not an observable!

$f(z)$: fragmentation functions (should be: “hadronisation functions”)

Peterson et al.

$$f(z) \propto \frac{1}{z(1 - \frac{1}{z} - \frac{\varepsilon}{1-z})^2}$$

→ estimation of transition matrix element by energy difference

Collins/Spiller

$$f(z) \propto (\frac{1-z}{z} + \frac{(2-z)\varepsilon}{1-z})(1+z^2)(1 - \frac{1}{z} - \frac{\varepsilon}{1-z})^{-2}$$

→ from correspondence to heavy meson structure functions

Kartvelishvili et al.

$$f(z) \propto z^\alpha(1-z)$$

→ from correspondence to different model of heavy meson structure functions

Lund symmetric

$$f(z) \propto \frac{1}{z}(1-z)^a \exp(-\frac{bm_t^2}{z})$$

→ symmetry wrt. start of string hadronisation at either end of the string

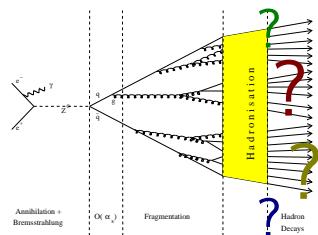
Bowler

$$f(z) \propto \frac{1}{z^{1+bm_t^2}}(1-z)^a \exp(-\frac{bm_t^2}{z})$$

→ constant probability per length and time for $q\bar{q}$ creation on the string

$$z = \frac{\text{energy of primary hadron}}{\text{energy of quark prior to hadronisation}} \text{ not directly measurable:}$$

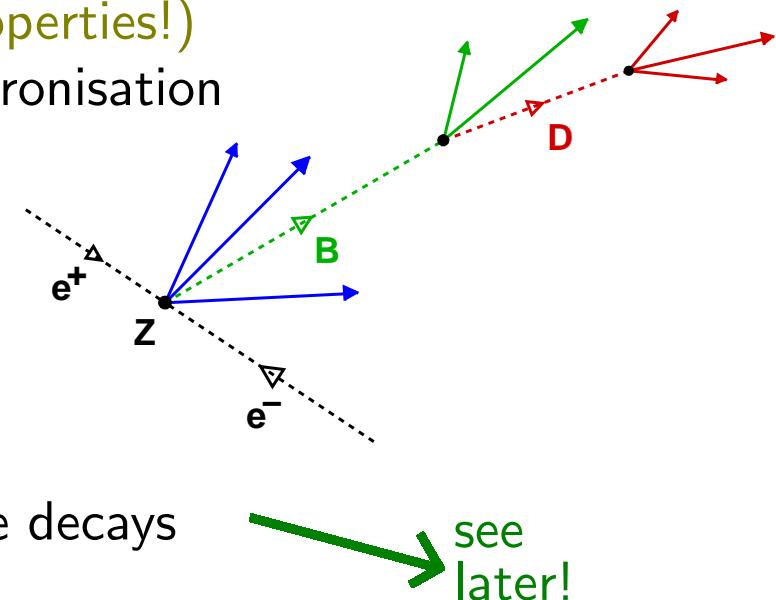
- energy of quark prior to hadronisation (*after fragmentation*) not observable
- further problem:



Which quark ends up in which hadron?

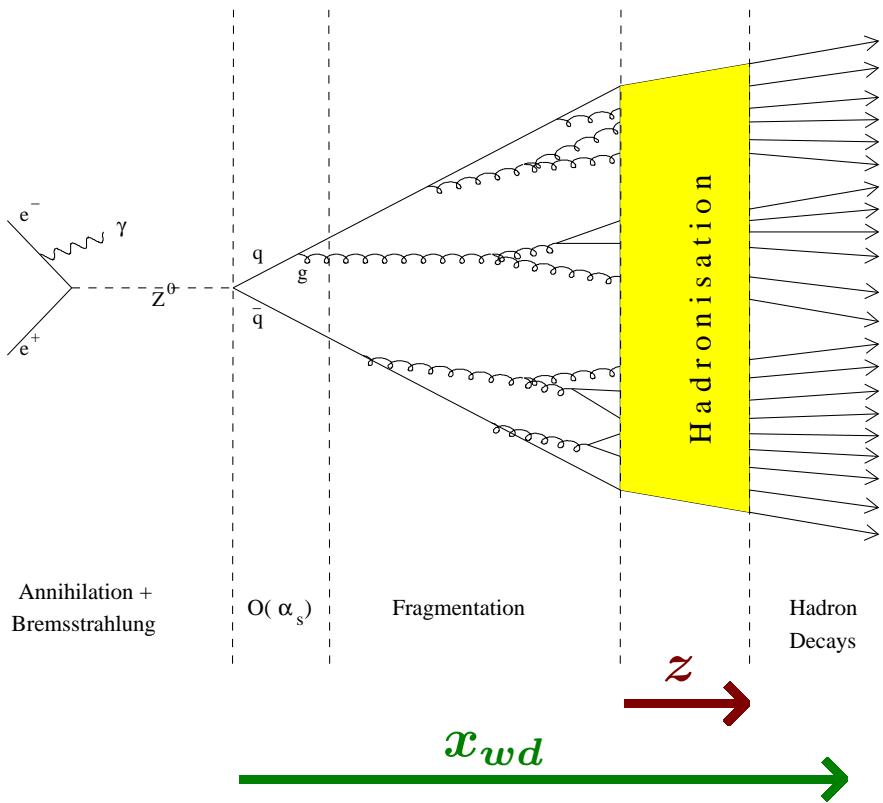
→ partial solution: consider **hadronisation of HEAVY quarks!**
(interesting anyway: specific properties!)

- no additional heavy quark creation during hadronisation
- hadron easily identified in weak decay
(lifetime, mass)



but: weakly decaying hadron \neq primary hadron
frequent creation of **excited** hadrons + cascade decays

Alternative variable: x_{wd}



$$z = \frac{\text{energy of primary hadron}}{\text{energy of quark prior to hadronisation}}$$

replace:

primary hadron

→ weakly decaying hadron

quark energy prior to hadronisation

→ energy at $q\bar{q}$ creation

(at 90 GeV: \approx beam energy)

$$x_{wd} = \frac{\text{energy of weakly decaying hadron}}{\text{beam energy}}$$

“scaled energy”

- measure energy distribution of weakly decaying hadrons
 correspondence to hadronisation model: Monte Carlo

Typical measurements of the B hadron energy distribution

reconstructed B hadrons	data sample	energy resolution
exclusive semileptonic decays ($B \rightarrow D^{(*)} \ell \nu$)	small	$\approx 5\%$
inclusive semileptonic decays ($B \rightarrow \ell + X$)	large	$> 10\%$
inclusive (decay vertices etc.)	very large	$\approx 10\%$

total number of B hadrons created at LEP: ≈ 2 million per experiment

SLD: ≈ 0.2 million

(TESLA GigaZ: several 100 million)

examples: recent measurements of the mean scaled energy $\langle x_{wd} \rangle$:

$B \rightarrow D^{(*)} \ell \nu$	ALEPH 2001	$\langle x_{wd} \rangle = 0.716 \pm 0.006(stat) \pm 0.006(syst)$
$B \rightarrow \ell + X$	OPAL 1999	$\langle x_{wd} \rangle = 0.709 \pm 0.003(stat) \pm 0.013(syst)$
inclusive	SLD 2002	$\langle x_{wd} \rangle = 0.709 \pm 0.003(stat) \pm 0.004(syst)$

→ inclusive analysis could improve OPALs contribution significantly

Energy distribution \iff hadronisation models

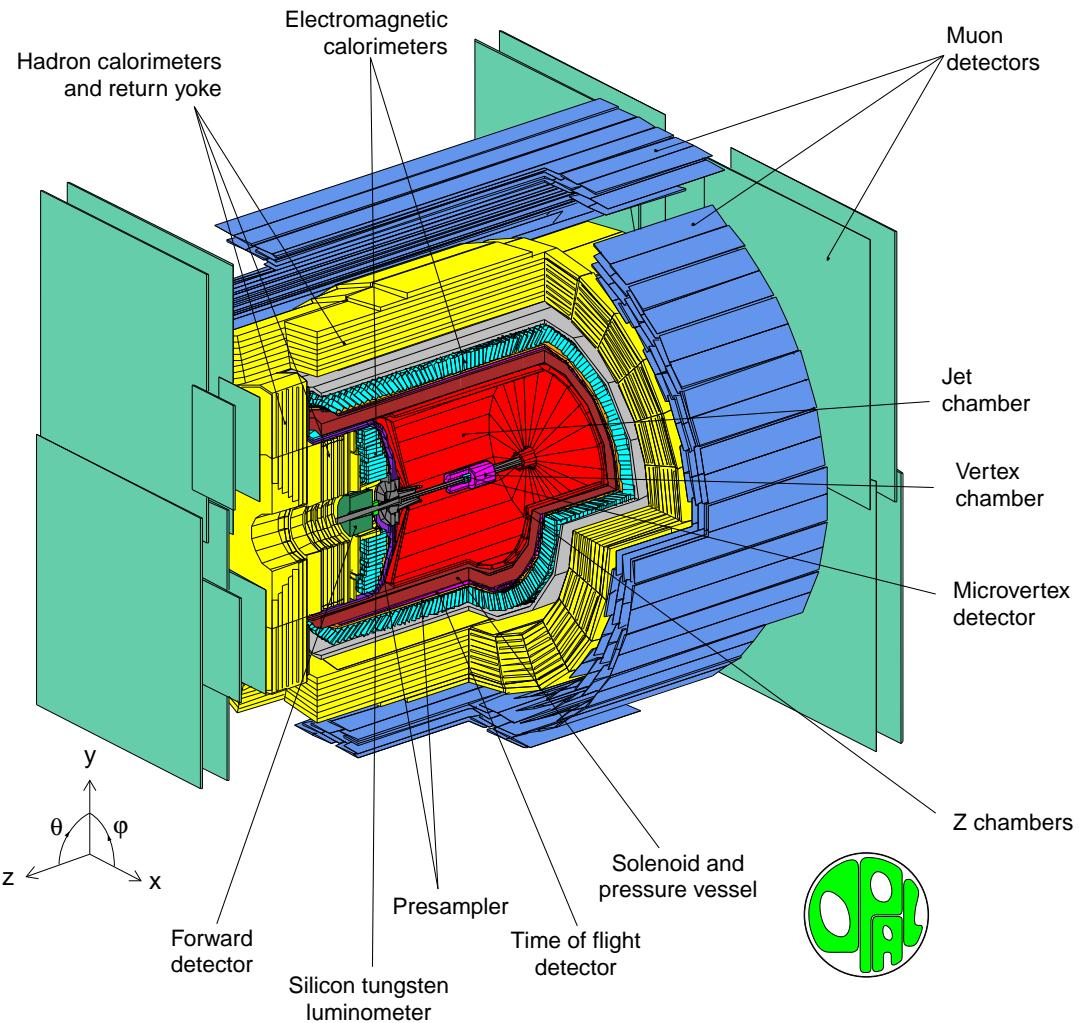
two main methods to derive information about hadronisation
from the hadron energy distribution:

- comparison of x_{wd} distribution with model predictions
- determination of model-independent parameters of the x_{wd} distribution
e.g. mean scaled energy, $\langle x_{wd} \rangle$

both methods used here

common basis of both analysis parts:
inclusive B hadron reconstruction

Largest common basis of the analysis parts: OPAL



vertex detector hit resolution

$$10 - 15 \mu\text{m}$$

momentum resolution

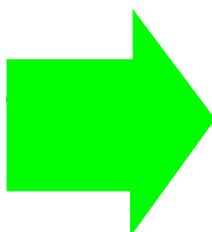
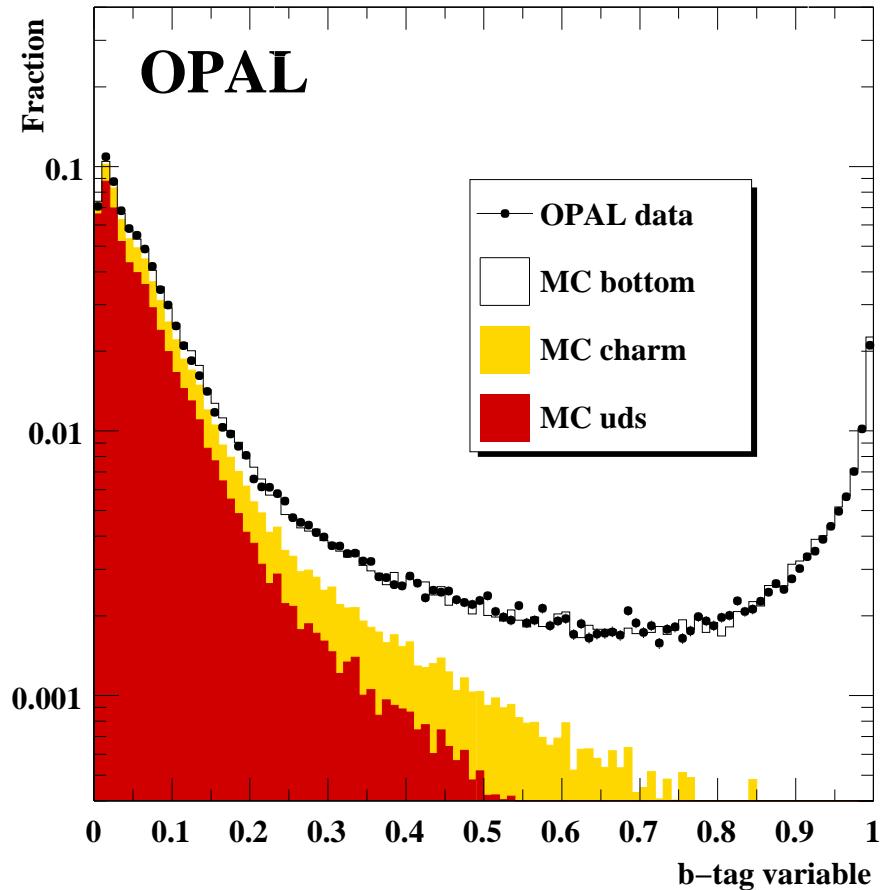
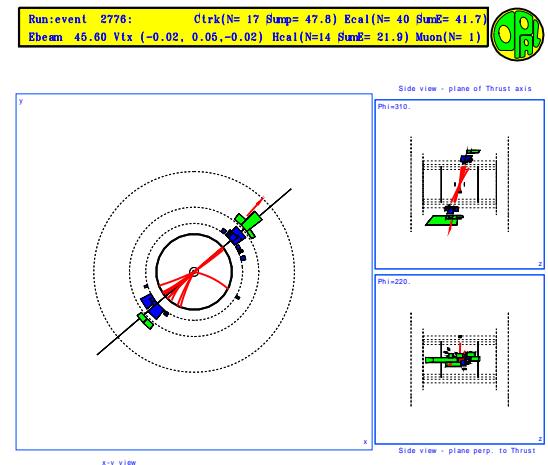
$$\approx 1.1 \times 10^{-3} (\text{GeV})^{-1}$$

jet energy resolution

$$\approx 95\% / \sqrt{E}$$

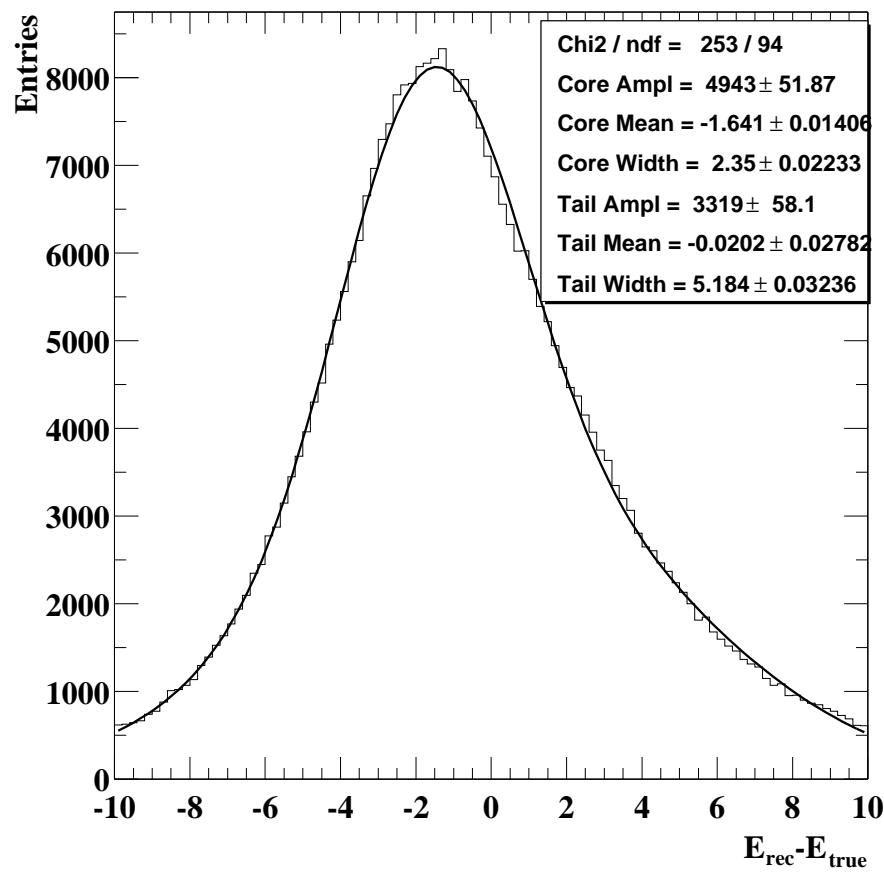
Selection and reconstruction of B hadrons

- selection of b jets
- reconstruction of B decay vertex
- selection of B hadron decay products
artificial neural nets identify tracks and clusters from B decays
- estimation of the B hadron energy
weighted sum over all selected tracks and clusters (weight = ANN output)

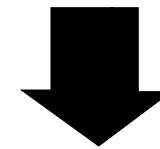


reconstruction efficiency: 16%
background contamination: 4%
energy resolution $\approx 10\%$

Energy resolution



good measurement of the B hadron energy



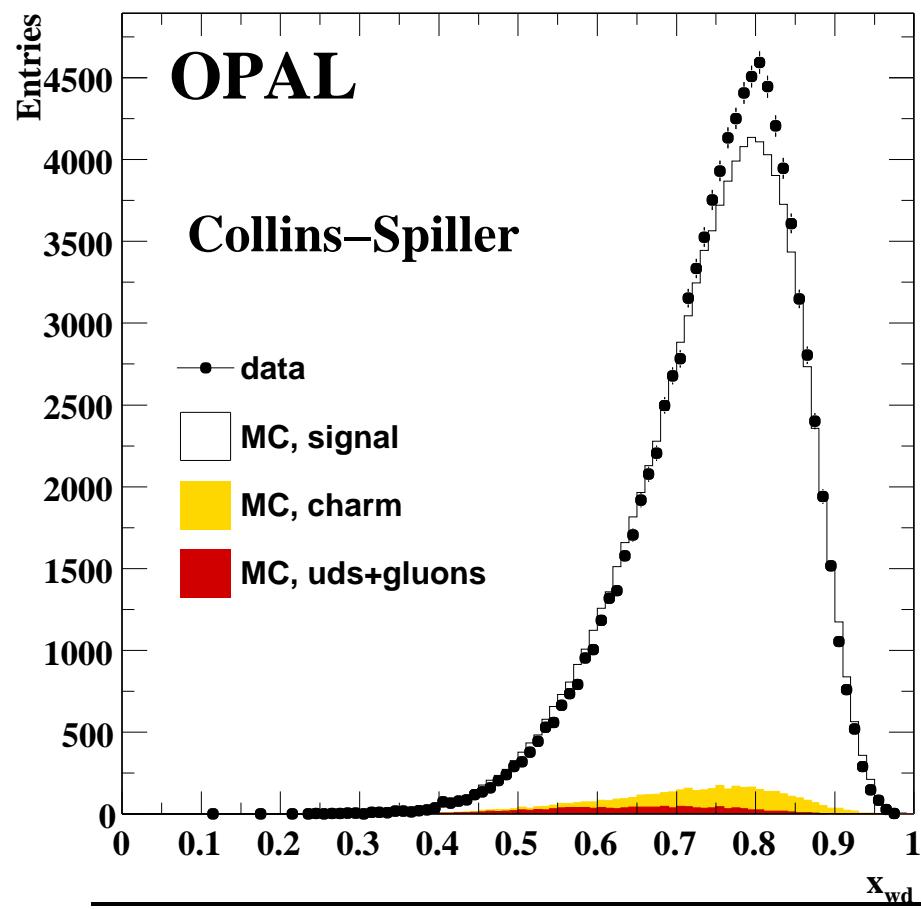
sensitive to hadronisation models

comparison of models with data:

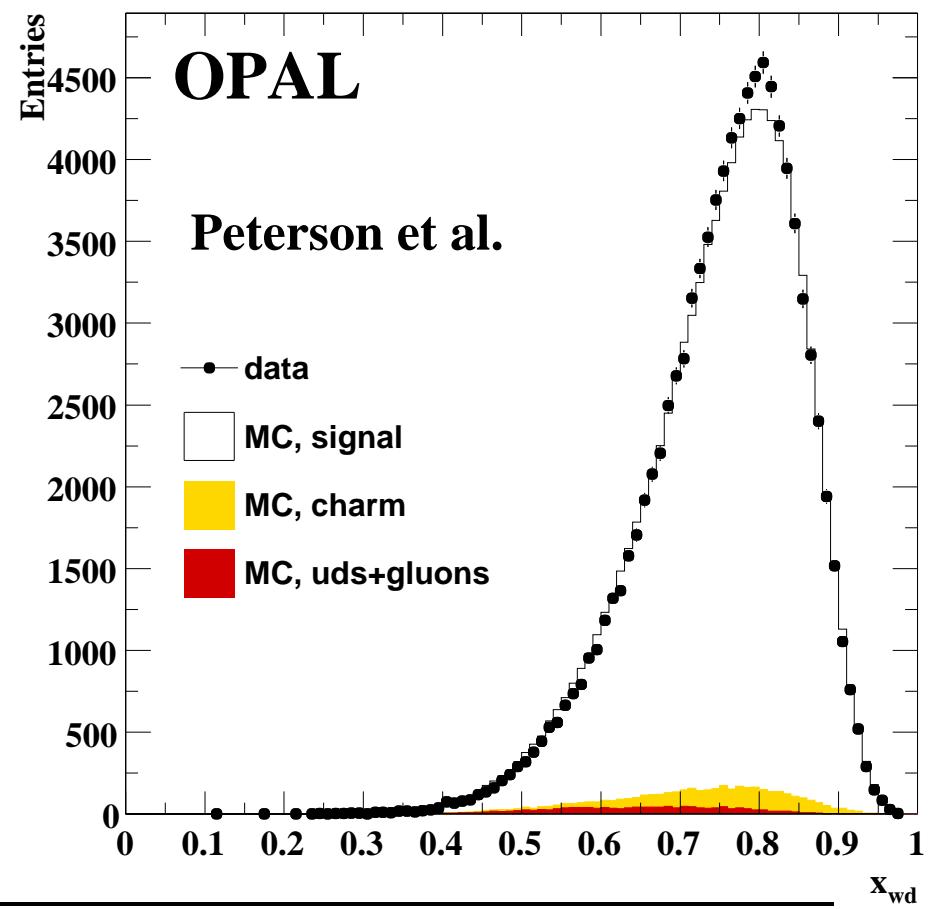
- tune important Monte Carlo parameters to data
- reweight $f(z)$ in Monte Carlo to desired fragmentation function
 - fit fragmentation function parameters to data

Model test results: Collins/Spiller, Peterson et al.

χ^2 : 407/45

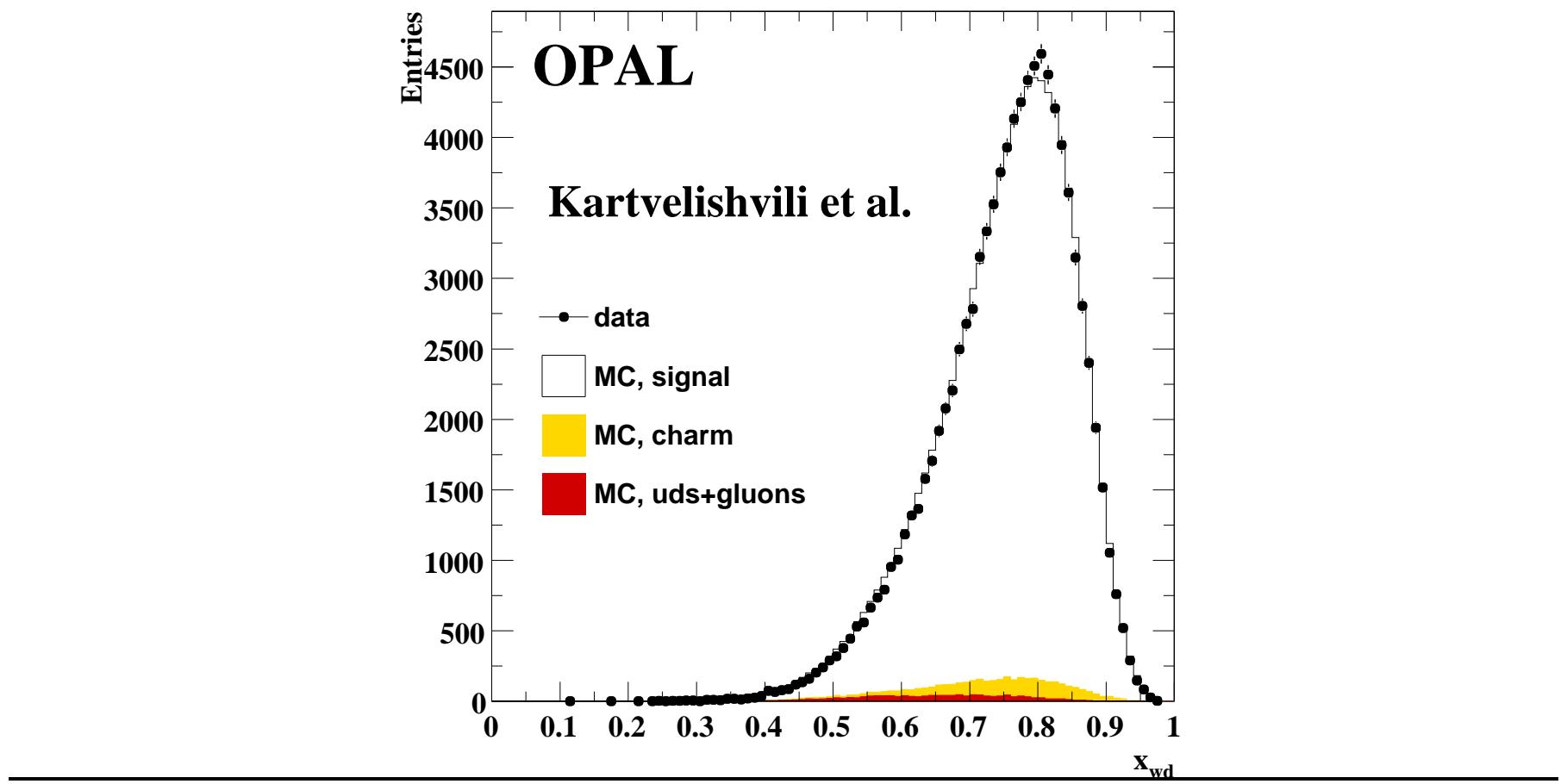


χ^2 : 159/45



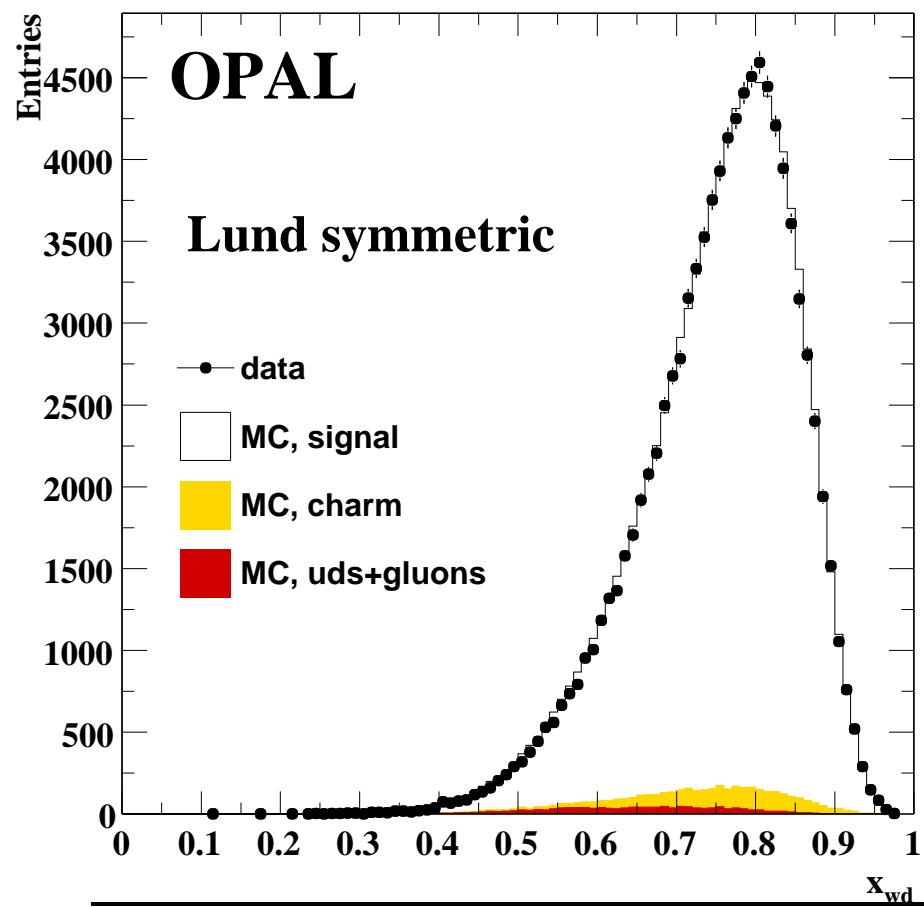
Model test results: Kartvelishvili et al.

$\chi^2: 99/45$

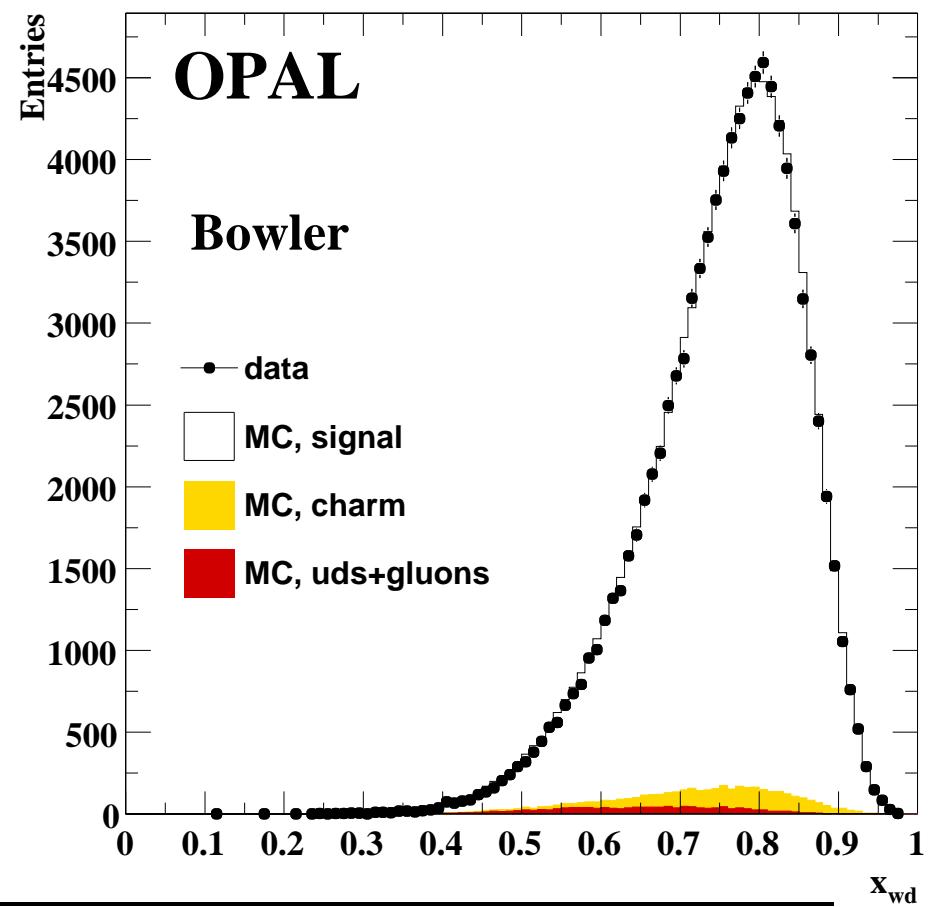


Model test results: Lund symmetric, Bowler

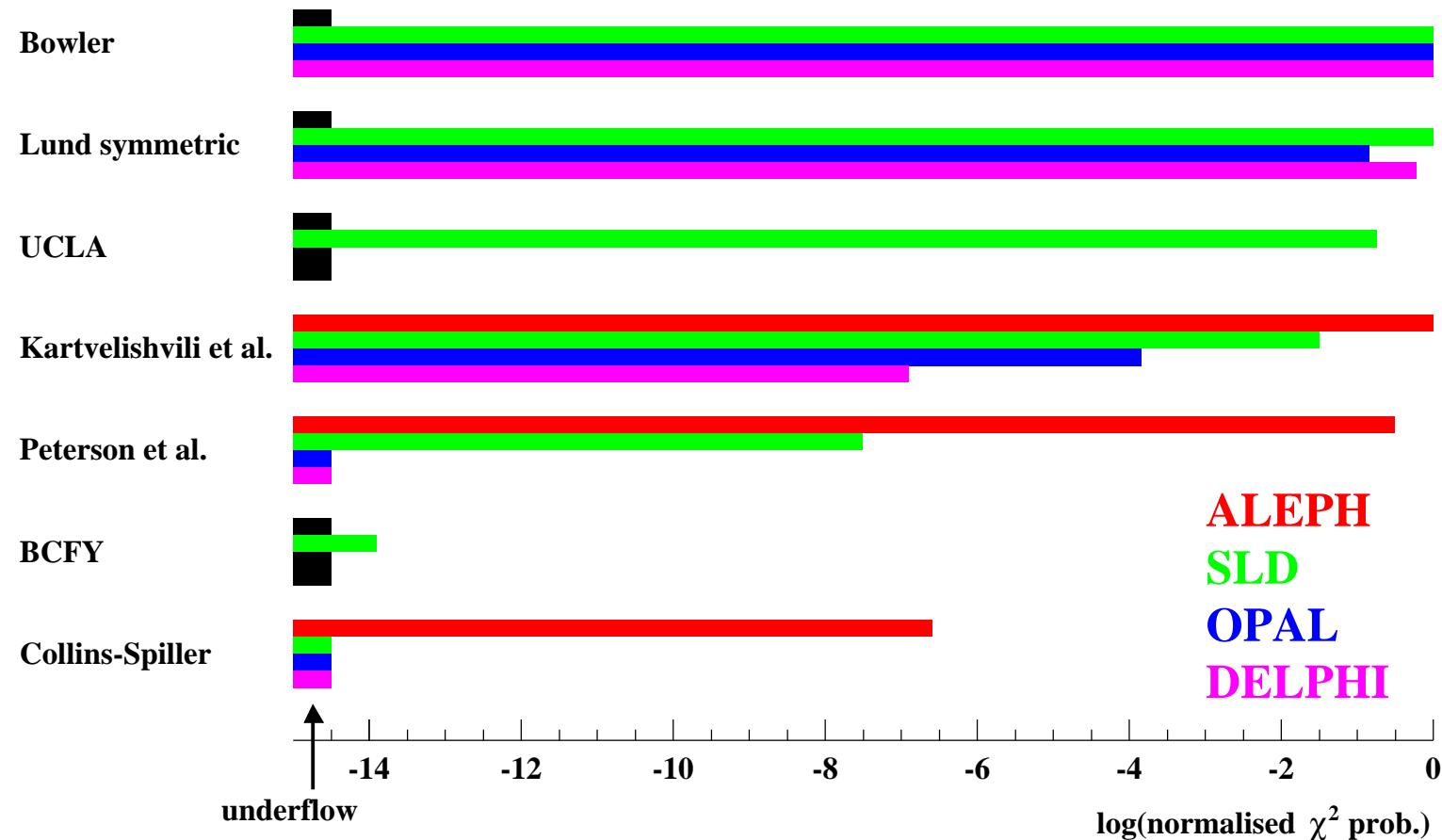
$\chi^2: 75/44$



$\chi^2: 67/44$



LEP/SLD 2001/2002: normalized $\chi^2/\text{d.o.f.}$ probabilities



same ranking seen by all experiments!

Herwig 5/6: tested by OPAL+SLD, but disfavored

Model-independent description of the B hadron energy spectrum

Fragmentation function parameters for specific models

- provide insufficient information for future model-builders
- depend strongly on (perturbative) fragmentation setup in MC
→ difficult to transfer results to e.g. hadron collider MC

instead:

describe B hadron energy distribution $D(x)$ in terms of moments

$$D_i = \int_0^1 dx \ x^{i-1} D(x)$$

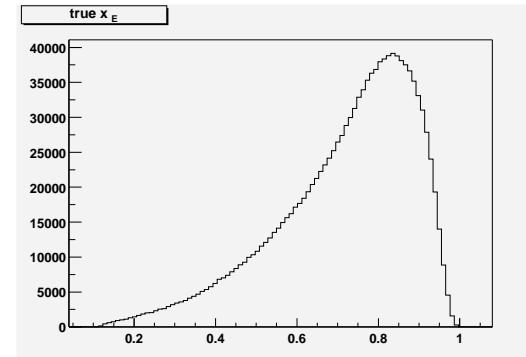
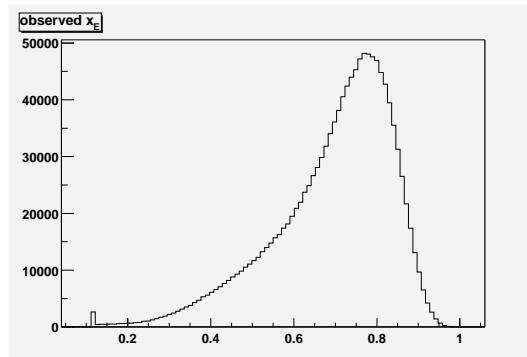
$$D_1 = 1, D_2 = \langle x_{wd} \rangle$$

Model-independent description of the B hadron energy spectrum

Cannot take moments from raw measured x_{wd} distribution:

- energy dependent efficiency
- finite detector resolution
- energy dependent reconstruction bias

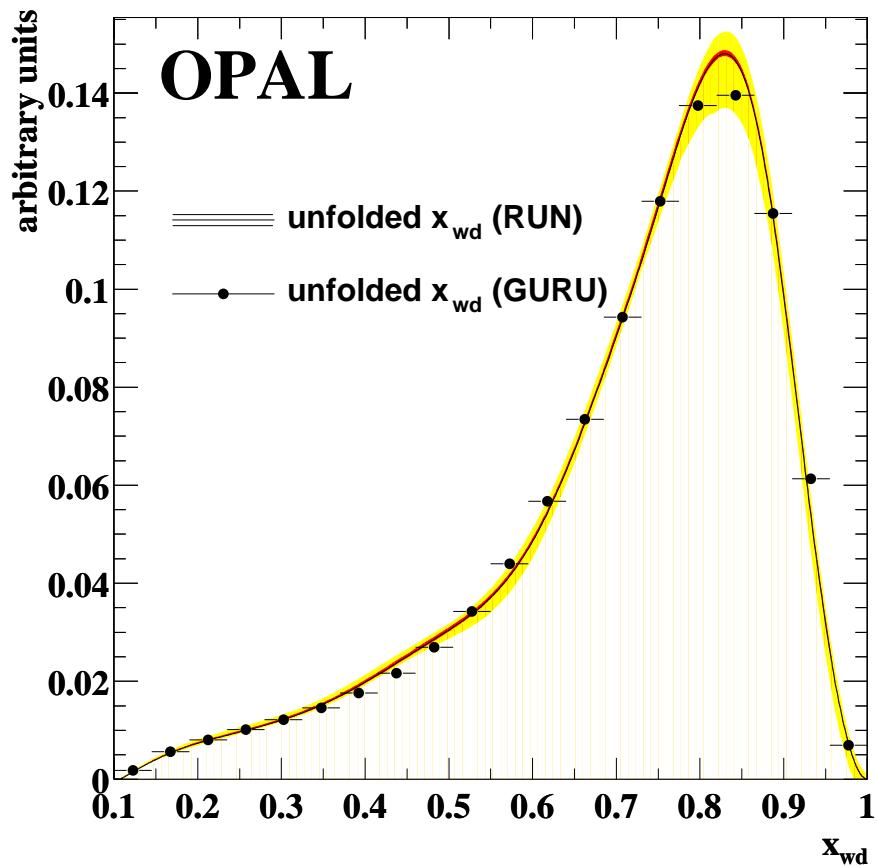
→ reconstruction of the true energy distribution by unfolding ←



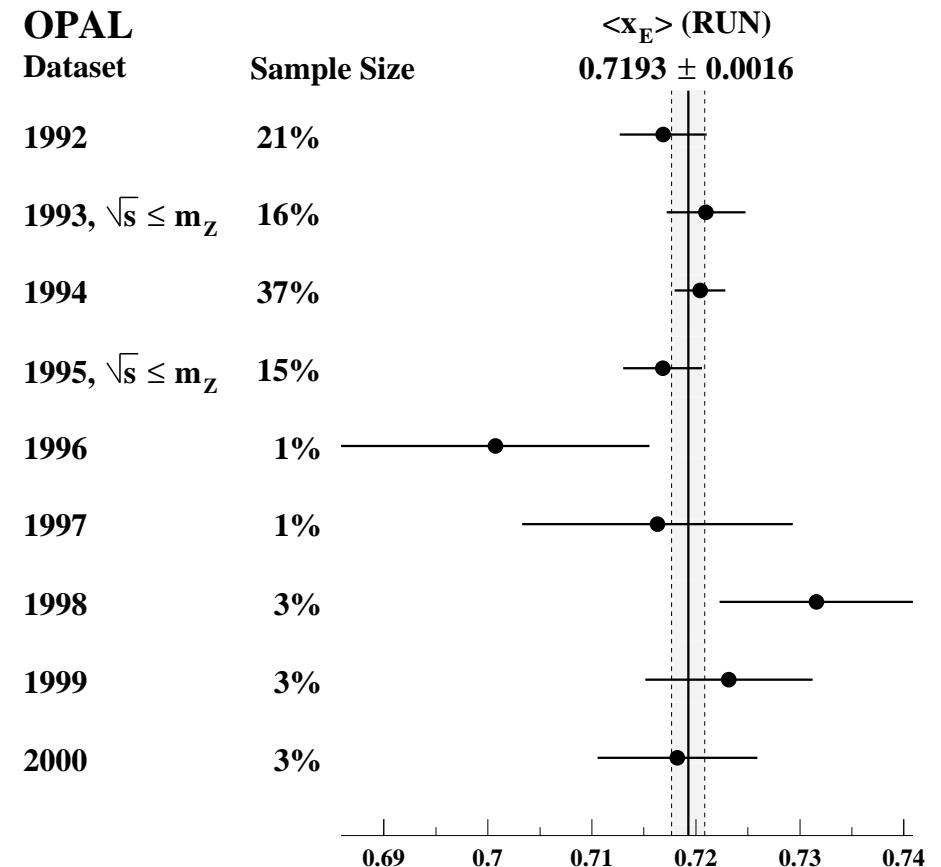
unfolding algorithms: RUN (Blobel), SVD-GURU (Kartvelishvili, Hocker)

Unfolded scaled energy distribution

unfolded energy distribution with error band



subsample consistency check



Unfolding result

mean scaled energy of weakly decaying B hadrons:

$$\langle x_{wd} \rangle = 0.7193 \pm 0.0016(stat)^{+0.0036}_{-0.0029}(syst)$$

dominant systematic uncertainties:

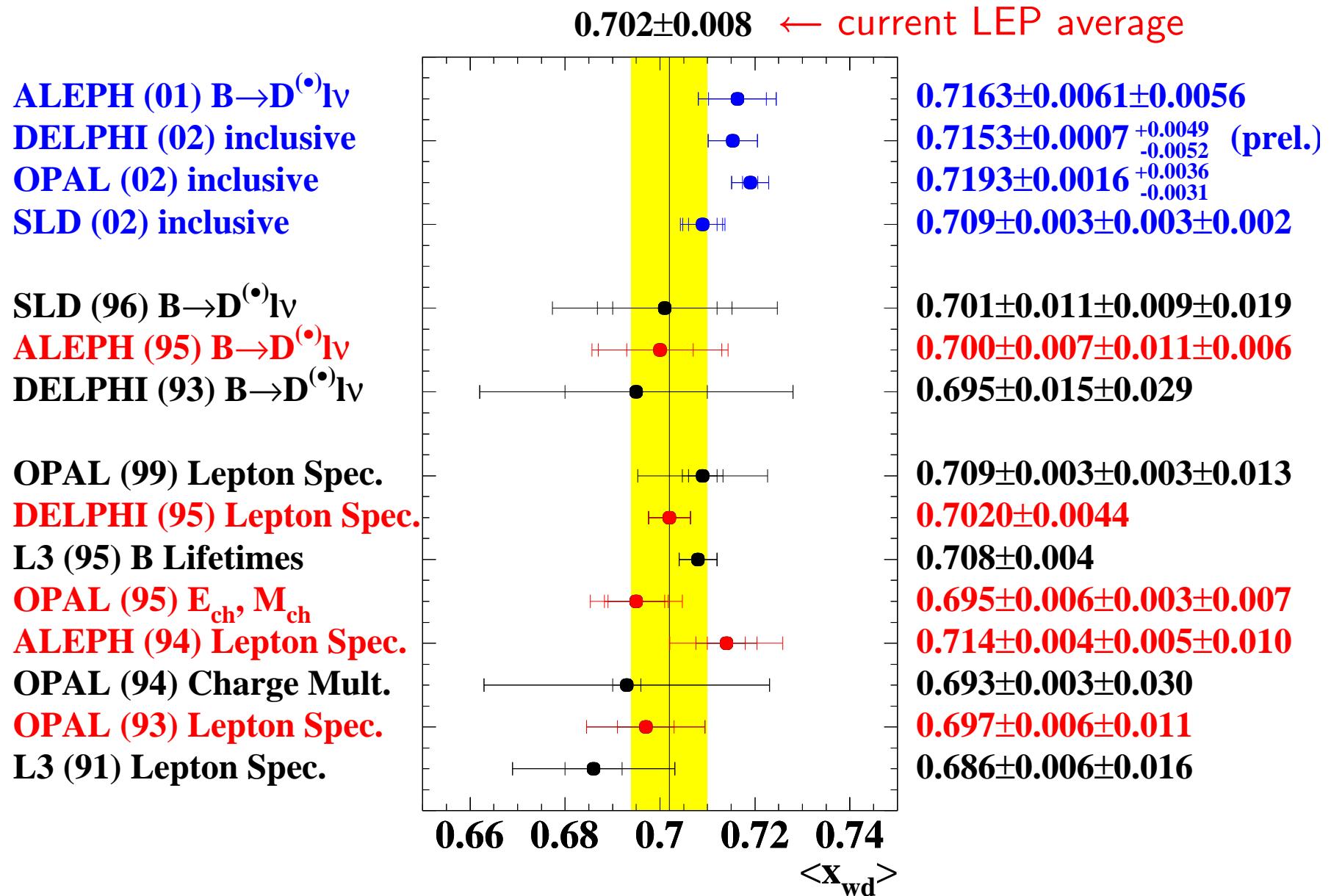
- detector resolution modeling (mainly calorimeter)
- unfolding with different MC types (detector simulation!)

very good agreement
with second unfolding method
 $(\langle x_{wd} \rangle = 0.7195 \pm 0.0015(stat))$

good agreement with model fit results

- | | |
|-----------------------|----------------------------------|
| Bowler | $0.7207 \pm 0.0008 \pm 0.0028$, |
| Lund symmetric | $0.7200 \pm 0.0008 \pm 0.0028$, |
| Kartvelishvili et al. | $0.7151 \pm 0.0006 \pm 0.0021$ |

Overview of $\langle x_{wd} \rangle$ measurements



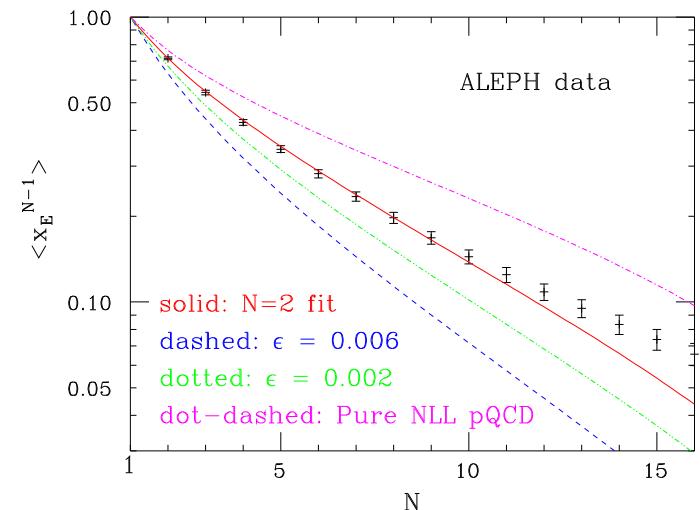
Towards the final LEP/SLD results

values from *very* preliminary
LEP/SLD combination
(P. Roudeau, E. Ben Haim):

$$\begin{aligned} D_1 &= 1 \text{ (definition)} \\ \langle x_{wd} \rangle &= D_2 = 0.7151 \pm 0.0025 \\ D_3 &= 0.5426 \pm 0.0012 \\ D_4 &= 0.4268 \pm 0.0010 \\ D_5 &= 0.3440 \pm 0.0017 \end{aligned}$$

Hadron colliders: $D_{4\pm 1}$ most important
Standard hadronisation models:

- very bad description of $D_{4\pm 1}$
- fit hadronisation parameters to moments,
not to x_{wd} shape
- less disagreement between $b\bar{b}$ cross-section
prediction and measurements (Cacciari et al.)

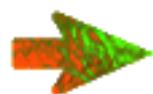


Summary: hadronisation of b quarks

very precise new LEP/SLD results
clear hierarchy of hadronisation models emerges

BUT:

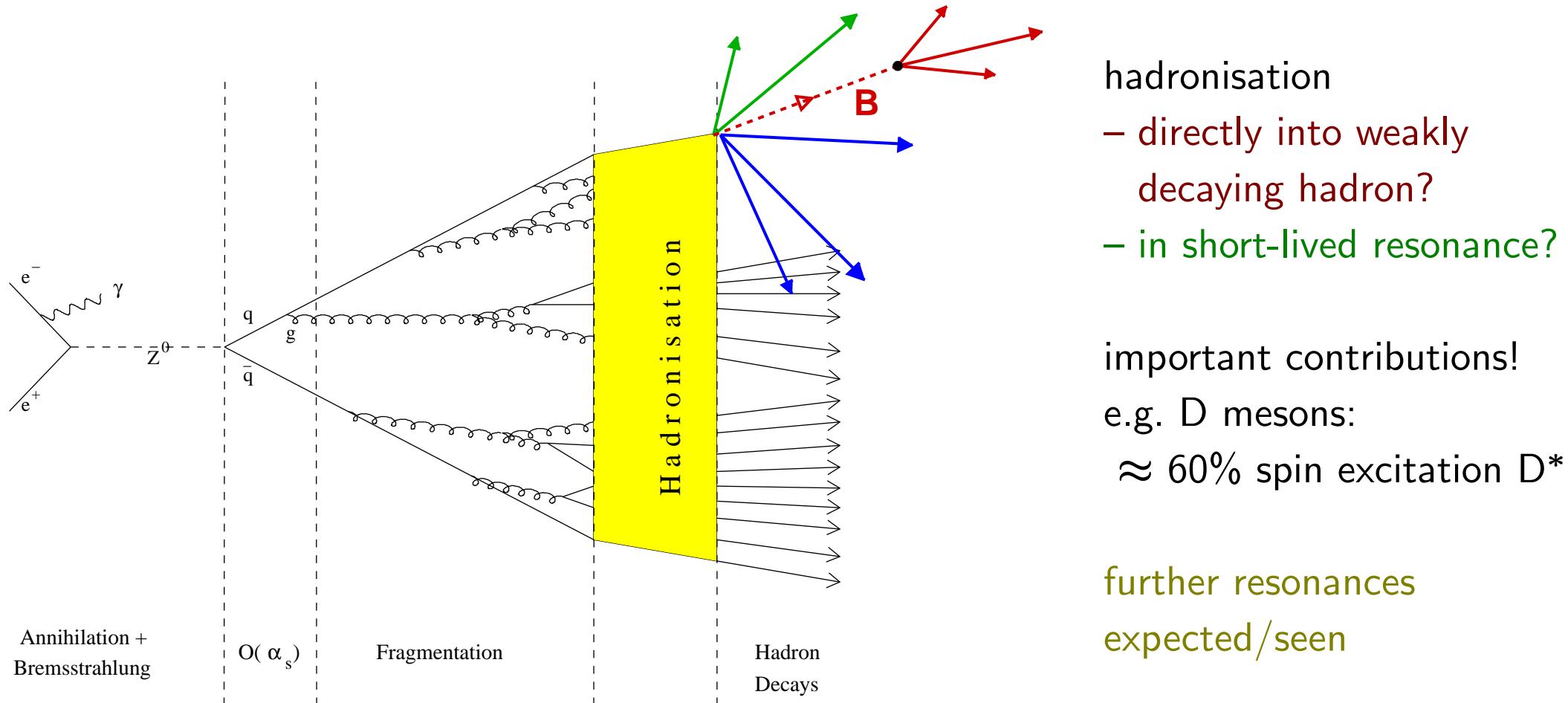
Do we really understand hadronisation now?



experimental precision: challenge for theory!

(by far not the only one...)

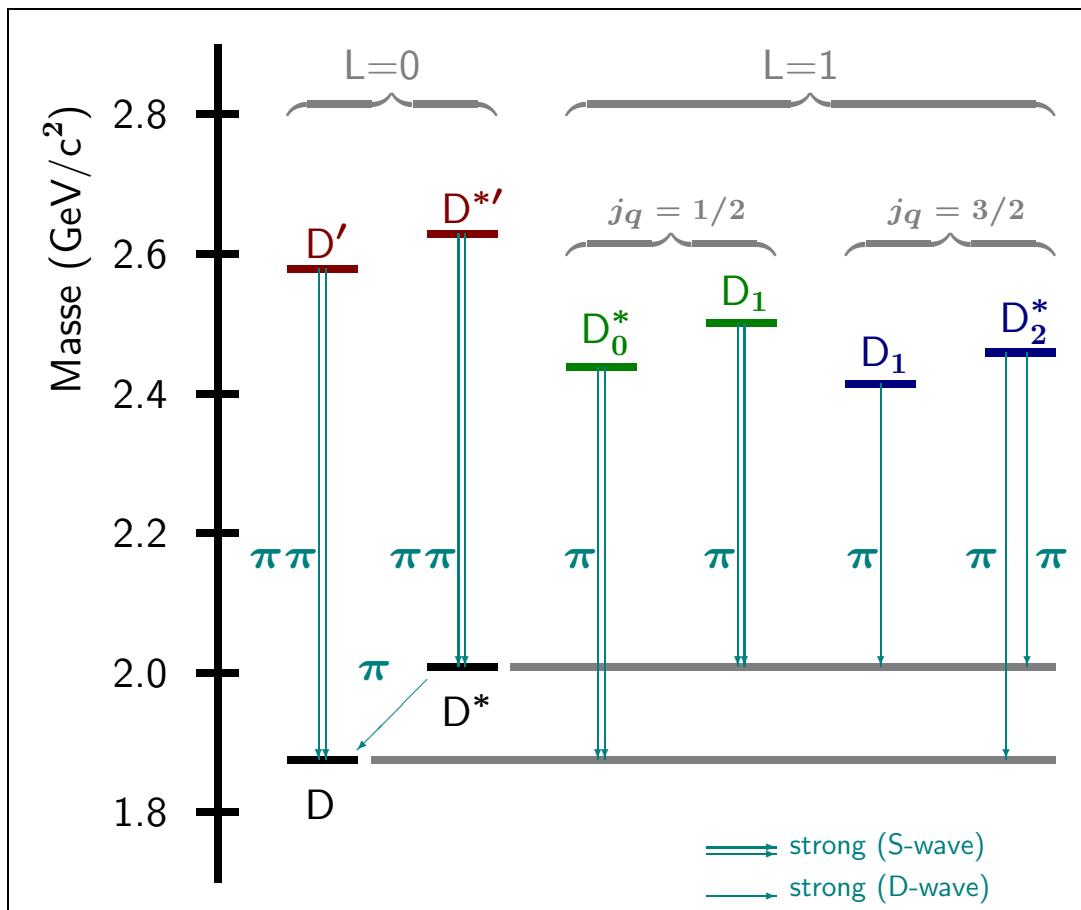
weakly decaying heavy hadron:
easy to identify (esp. B hadrons)



- interesting field:
- production rates → insight into hadronisation process
 - properties (mass, width) → interaction of quarks in hadrons

Interaction of quarks within hadrons: dominated by QCD, usually non-perturbative
→ only special cases calculable, e.g.

D mesons



S-wave: typical width ≈ 100 MeV

D-wave: typical width ≈ 10 MeV

mass calculations: precise
width, production rates: difficult

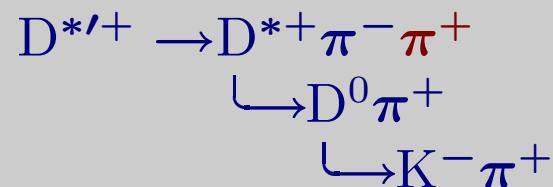
strong decays, emission of π , $\pi\pi$

narrow orbital excitations (D_1 , D_2^*):
seen in $D^{(*)}\pi$ → see this talk

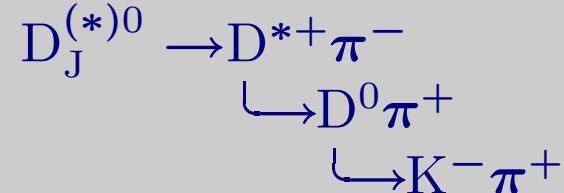
radial excitation $D^{*''}$:
seen in $D^*\pi\pi$ (4.7σ , DELPHI),
width < 15 MeV ??? → see this talk

Reconstruction of excited D mesons at OPAL

radial excitation:



orbital excitations:



reconstruction method:

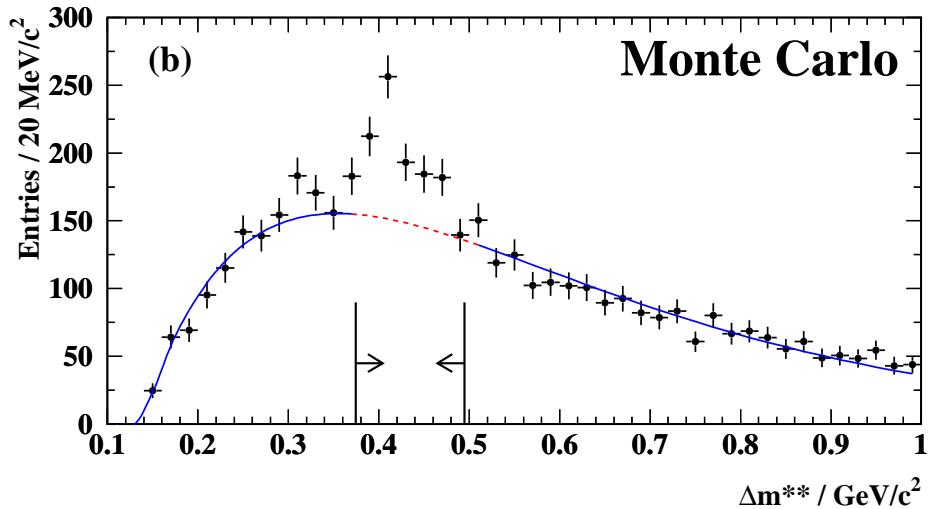
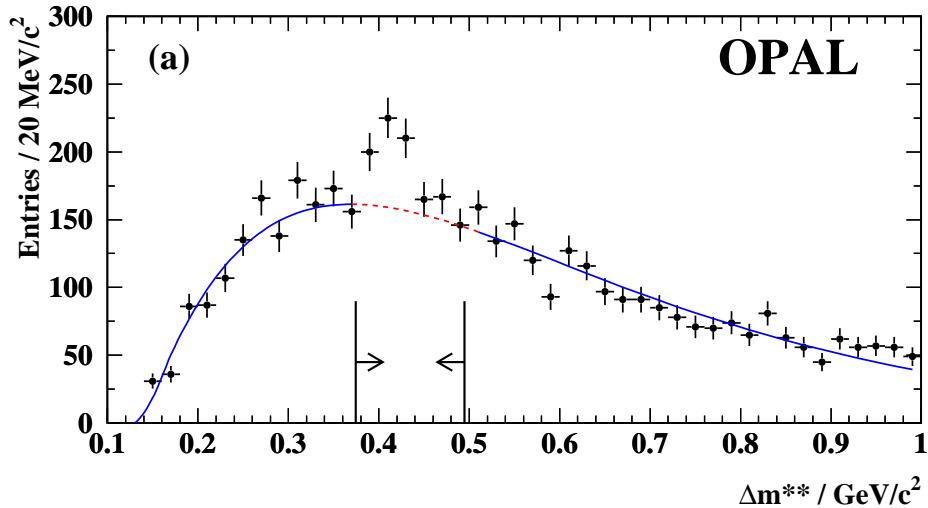
candidate = arbitrary combination of tracks fulfilling the following criteria:

selection criteria:

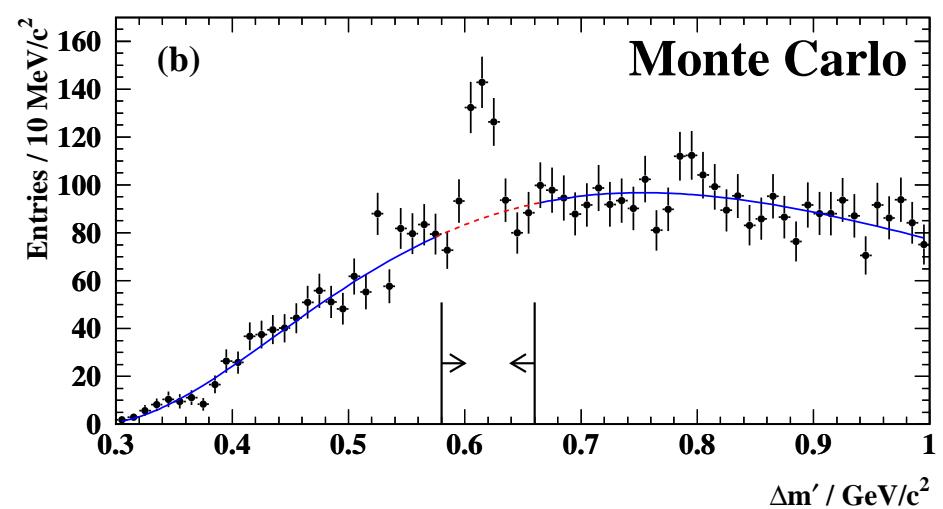
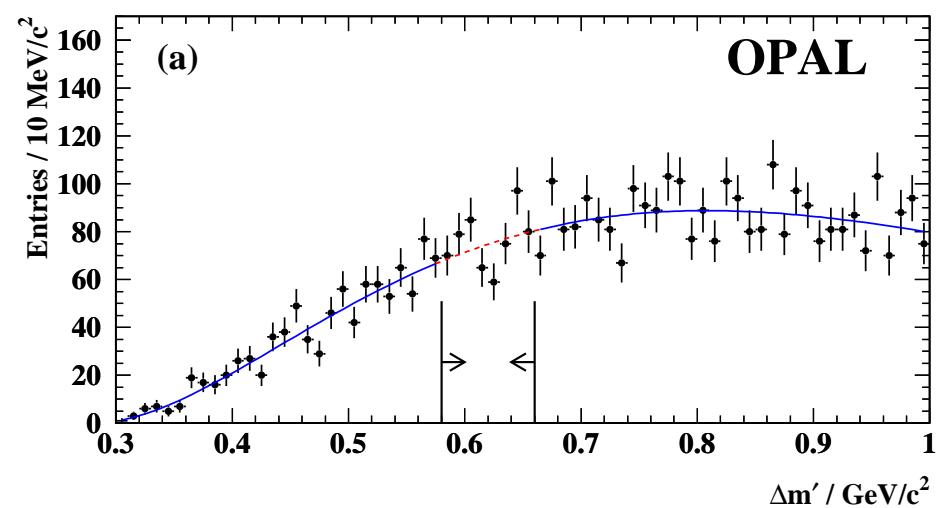
- correct charge combination
- masses of D^{*+} and D^0 in expected range
- helicity angle of D^0 decay in region with small background
- kaon identification (jet chamber dE/dx)
- mesons from c hadronisation: energy above large threshold
- mesons from b decays: decay length

Selection results

orbital excitations



radial excitation?



Limits on D^{*+} production rates

95% C.L.; assumption: width as measured by DELPHI

in hadronic Z decays:

$$f(Z \rightarrow D^{*+\pm}) \times \text{Br}(D^{*+\pm} \rightarrow D^{*+}\pi^+\pi^-) < 0.31\%$$

in c hadronisation:

$$f(c \rightarrow D^{*+}) \times \text{Br}(D^{*+} \rightarrow D^{*+}\pi^+\pi^-) < 0.9\%$$

in b decays:

$$f(b \rightarrow D^{*+}) \times \text{Br}(D^{*+} \rightarrow D^{*+}\pi^+\pi^-) < 2.4\%$$

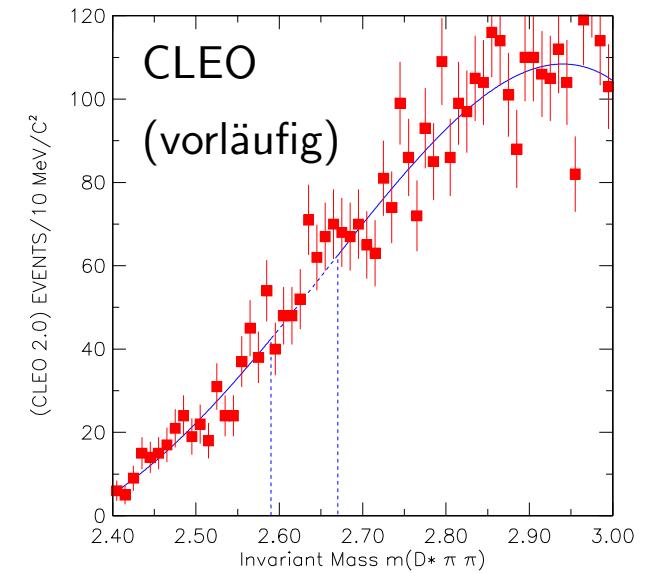
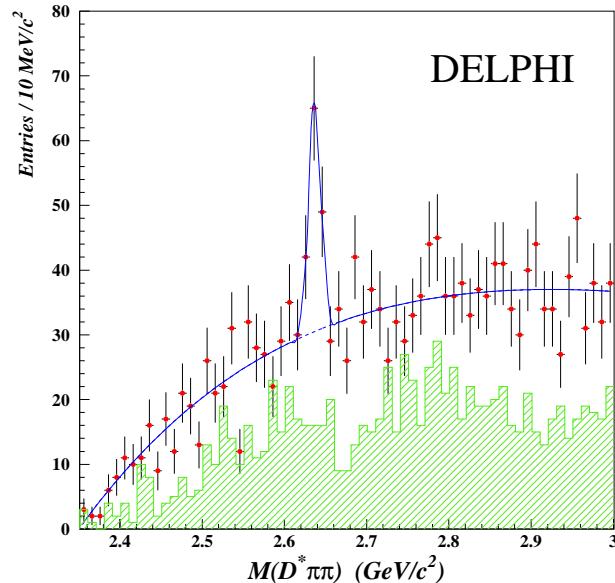
normalized to production rate of narrow orbital excitations:

$$R < 0.22$$

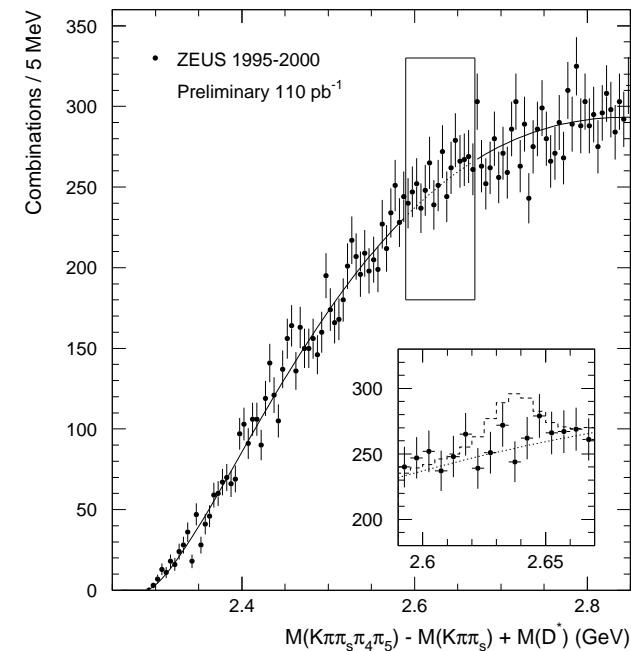
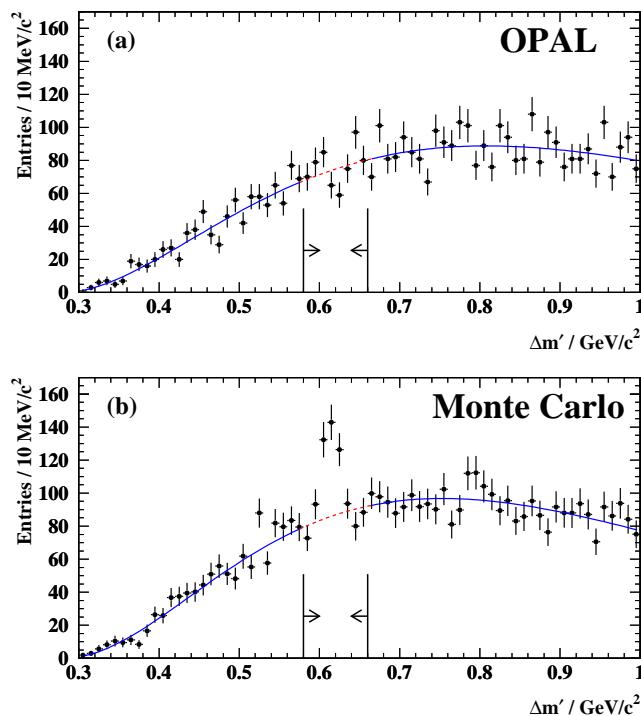
DELPHI: $R = 0.49 \pm 0.18(\text{stat}) \pm 0.10(\text{syst})$

Global picture

radially excited
D mesons:
DELPHI measurement
not confirmed

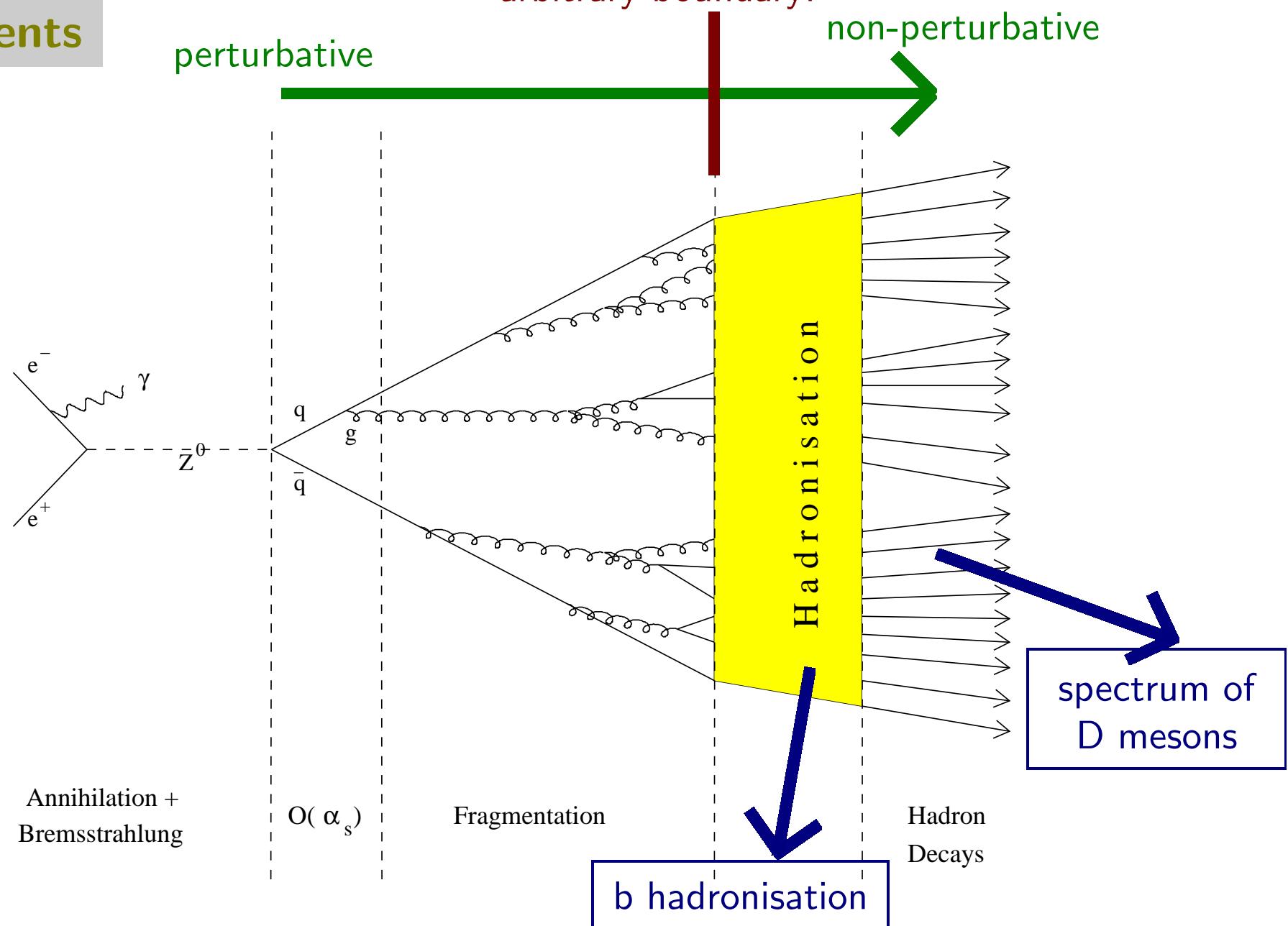


private communication:
no resonance seen
in BELLE data



Hadronic e^+e^- events

factorisation at
arbitrary boundary!



What did we learn?

hadronisation of b quarks

- hierarchy of models established
- most precise measurement of the B hadron energy spectrum:
precision improved by a factor of 2.5 resp. 4
with respect to previous OPAL measurements on same dataset
- reduction of systematic uncertainties of analyses involving heavy flavors

D meson spectroscopy

- narrow orbital D excitations seen in data (but: clear detector limitations)
- radial D excitation: no narrow resonance found at OPAL, CLEO, ZEUS